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Wilson C. Chin

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THE TRANSONIC OSCILLATING FLAP

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I ABSTRACT

Numerical experiments for the unsteady transonic flow past a symmetric airfoil with an oscillating flap in free air are carried out for a range of supercritical Mach numbers and reduced frequencies using two newly devised computational schemes. The inviscid results, unhampered by the complicating effects of wind tunnel wall interference and shockwave and boundary layer interaction, evaluate the extent to which the unsteady loading responds linearly to changes in flap deflection and also the dependence of shock excursion amplitude and net unsteady lift and moment coefficients on oscillation frequency. The main conclusions are discussed in light of recent experimental findings.

II INTRODUCTION

A characteristic of transonic unsteady flow with shockwaves is the potentially large phase lag between boundary motion and induced surface pressure. Moreover, net force coefficients generally exceed those in subsonic and supersonic speed regimes. These effects tend to increase the likelihood of aeroelastic instability, making transonic speeds most critical for aircraft flutter. Landahl's classic monograph [1] addresses the basic physical and mathematical issues, emphasizing tractable linear models.

The inherent nonlinearity of the problem obviously forbids general analysis. However, two somewhat limited numerical capabilities currently exist. The first analyzes the unsteady loading induced by small amplitude oscillations using a relaxation solution of the mixed-type time Fourier transformed disturbance equation which results from linearization about a prescribed steady nonlinear mean flow and applies to motions of arbitrary frequency [2]. The second, somewhat more general, integrates the governing small disturbance equation in time using an efficient alternating-direction-implicit factorization, but with a restriction to low-frequency motions [3]. Shortcomings are present in each of these methods. In the first case the nonharmonic part of the total disturbance flow is artificially fixed and taken as the steady solution that obtains when no forced oscillations are present: the required nonlinear feedback and energy transfer from harmonic components to mean flow, accounted for in direct time integration methods, which depend on both oscillation frequency and amplitude, are completely neglected. This linearization is probably valid for sufficiently high reduced frequencies, of course, but the extent to which this validity holds for large deflection amplitudes is not clear. In the second case the neglect of high-frequency terms, while self-consistent for small reduced frequencies, renders the treatment of

fast oscillations and gust-like responses impossible. The confidence we attach to low-frequency results, not to mention the exact consequences of small disturbance theory without restrictions to the degree of unsteadiness, are of obvious engineering interest.

In this paper two numerical methods are devised, the first extending the work of [2] to account for the "back-interaction" of the primary harmonics on the nonharmonic mean flow, and the second extending the ADI method of [3] to handle general unsteady motions. These algorithms, used here to resolve the issues formerly cited, e.g., the linearity of the unsteady load response to changes in surface deflection, the influence of frequency on shock excursion and mean shock location, etc., aim at increasing our present understanding of unsteady nonlinear interactions. Apart from their fundamental interest, these problems are important in engineering.

However we deal only with oscillating trailing edge flaps as opposed to pitching motions of rigid airfoils. We stress that these examples are physically distinct and qualitatively different. In the former case the mean flow is roughly fixed throughout the unsteady motion in the sense that supersonic zones terminated by shock waves appear on both upper and lower surfaces. In contrast, for pitching oscillations at moderate angles, each chordwise surface alternates between shockfree subcritical and supercritical shocked flow states. Thus, to a certain degree, flap induced effects are higher-order. Qualitative results and trends obtained here for flapping oscillations generally do not apply to pitching motions, but they may be typical of flapping motions in general and therefore of useful design interest.

III ANALYSIS

Time-Marching ADI Method

Accurate solutions for instantaneous shock strength and position are needed to calculate net forces and moments, since the departure of the shock from its mean position produces an additional local lift contribution proportional to the strength of the steady shockwave and the differential upper and lower surface shock motion. These are also essential to the analysis of unsteady viscid-inviscid interactions and transonic aileron buzz. We therefore formulate the numerical problem for general unsteady motions, however, within the framework of transonic small-disturbance theory. Consider the nondimensional equation $Aa\phi_{\tau\tau} + 2B\phi_{\xi\tau} = C\phi_{\xi\xi} + \phi_{\eta\eta}$ where ϕ is the disturbance velocity potential normalized by $U_\infty c\,\delta_0^{2/3}$, c is the chord, U_∞ is the freestream speed at infinity and δ_0 is the maximum thickness to chord ratio. Let ω be the oscillation frequency and define a reduced frequency by $k = \omega c/U_\infty$. If M_∞ is the freestream Mach number, the required coefficients are $A = k^2M_\infty^2 / \delta_0^{2/3}$, $B = kM_\infty^2 / \delta_0^{2/3}$ and $C = (1-M_\infty^2)/\delta_0^{2/3} - (\gamma+1)M_\infty^2\phi_\xi$, where $\gamma = 1.4$ is the ratio of specific heats, nondimensional variables having been assumed in the form $\tau = U_\infty kt/c$, $\xi = x/c$ and $\eta = \delta_0^{1/3}\,y/c$, x, y and t being streamwise, transverse and time coordinates. Consistent boundary conditions are the specification of $\phi_\eta(\xi, 0^\pm, \tau) = f_\xi^\pm + akf_\tau^\pm$ on the chord $0 \leq \xi \leq 1$, where $f^\pm$ is the instantaneous airfoil displacement normalized by δ_0, pressure continuity across the trailing edge wake (the pressure coefficient is evaluated from $C_p = -2\,\delta_0^{2/3}(\phi_\xi + ak\phi_\tau)$) and vanishing disturbance velocities at infinity. Note that a = 0 in the low-frequency approximation and a = 1 in the general case.

Solutions to the governing equation are obtained by an alternating-direction-implicit scheme which advances the solution for ϕ at each meshpoint from time level τ_n to τ_{n+1} through the sequential procedure

$$\xi\text{ - sweep:}\qquad \frac{2B}{\Delta\tau}\,\delta_\xi(\tilde{\phi}-\phi^n) = D_\xi g + \delta_{\eta\eta}\phi^n$$

$$\eta\text{ - sweep:}\qquad \frac{Aa}{(\Delta\tau)^2}\left\{\phi^{n+1}-2\phi^n+\phi^{n-1}\right\} + \frac{2B}{\Delta\tau}\,\delta_\xi(\phi^{n+1}-\tilde{\phi}) = \frac{1}{2}\,\delta_{\eta\eta}(\phi^{n+1}-\phi^n)$$

where $g = \frac{1}{2}(C^n\tilde{\phi}_\xi + (1-M_\infty^2)\,\phi_\xi^n / \delta_0^{2/3})$. In the low-frequency limit our decomposition, dubbed GTRAN2, reduces to the LTRAN2 method of [3]. This latter method is $O(\Delta\tau^2)$ accurate and unconditionally stable on a von Neumann basis. For general unsteady motions the present scheme consistently approximates the given equation with $O(\Delta\tau)$ accuracy; while not unconditionally stable, it appears to be reliable and instabilities have not been observed. Here $\delta_{\eta\eta}$, δ_ξ and D_ξ are the central, backward and mixed difference operators defined in [3] ; for brevity details related to tangency, wake, shock and farfield conditions, being straightforward modifications to LTRAN2, will not be discussed.

Nonlinear Harmonic Method

For small amplitude oscillatory airfoil motions the harmonic method of [2] is adequate. However, for larger surface deflections, nonlinear frequency expansions must be used to account for the back-interaction of the primary harmonics on the mean flow. On physical grounds the "mean" or, more precisely, the nonharmonic part of the total disturbance flow "freezes" for sufficiently fast oscillations [1]. Thus the dominant effects of nonlinear feedback are felt only for low-frequency motions, where large shock excursions are also anticipated, and we consistently set a=0. For unsteady

transonic flows the basic approach to modeling this back-interaction was first described by the present author in [4]. Essentially the disturbance potential (and likewise, the unsteady airfoil displacement) is expanded in the form $\phi(\xi,\eta,\tau) = \phi_0(\xi,\eta) + \frac{1}{2}\varepsilon(\phi_1 e^{i\tau} + \bar{\phi}_1 e^{-i\tau}) + \ldots$ where higher harmonic terms are not shown, $\bar{\phi}_1$ is the complex conjugate of $\phi_1(\xi,\eta)$, and ε is proportional to the oscillation amplitude, and substituted into the governing equations. For small amplitude motions a sequence of problems can be obtained by equating coefficients of like powers of ε; this results in the usual steady nonlinear formulation for ϕ_0 and a linearized problem for ϕ_1 (e.g., see [2]). As previously discussed this expansion is not uniformly valid in time: the mean flow is artificially frozen because ϕ_0 does not depend on k or ε. For slightly larger ε this usage degenerates even more and fallacious results are possible. This defect is remedied by equating, instead, coefficients of like harmonics, in which case an infinite system of nonlinearly coupled equations for the ϕ_j is obtained. To leading order the effects of secondary and tertiary harmonics can be neglected. Thus the resulting equation for ϕ_1 is formally identical with the ϕ_1 equation obtained by straightforward linearization; however, the ϕ_0 coefficients are formally unknown because the equation for the "mean flow" ϕ_0 now contains an additional term of the form $\partial|\phi_{1_\xi}|^2/\partial\xi$ which furnishes the required nonlinear coupling. Although this term is formally $O(\varepsilon^2)$ it <u>may</u> exert a cumulative $O(\varepsilon)$ influence, especially near shockwaves. The resulting equations for ϕ_0 and ϕ_1 are solved iteratively, in each case using the mixed-differencing column relaxation described in [2]. A trivial solution first initializes the calculations. One computational "sweep" of the flowfield solves the ϕ_0 equation subject to mean boundary conditions and an assumed zero ϕ_1. Next

the ϕ_1 equation is solved with unsteady boundary conditions and latest available ϕ_0 values, followed by a solution of ϕ_0 using latest ϕ_1 values, and so on. Apart from the noted change to the ϕ_0 equation, details related to body and wake conditions, shock capture and farfield updates follow [2] and will not be rediscussed here. We indicate the slow convergence of the method, however.

IV RESULTS

Time-marching solutions for an unpitched symmetric NACA 64A010 airfoil section at Mach 0.82 were made for an aft quarter-chord flap with the angular deflection history $\alpha(\tau) = 1^{o}\sin\tau$ at reduced frequencies k = 0.05, 0.5 and 5.0. All time integrations were initialized with a steady flow and marched over four periods to rid solutions of undesired initial transients. GTRAN2 and LTRAN2 results were obtained using identical fine spatial meshes, and time steps were chosen in each case such that truncation terms were formally of the same order. Computed unsteady shockwave positions appear in Figure 1. The shock excursions obtained in both GRTAN2 and LTRAN2 modes for the lower surface are similarly sinusoidal (second harmonic effects are not visually perceptible). Both suggest a mean shock location at 56% chord independent of frequency and recover, in agreement with Landahl [1], the shock motion freeze that obtains in the limit of large reduced frequency. Moreover GTRAN2 and LTRAN2 results are not significantly different, although the latter overpredicts the peak excursion amplitudes somewhat. In the k = 0.05 case the unsteady shock traverses a net distance of 18% chord, a situation that may be critical to acceptable boundary layer behaviour. The corresponding net lift and moment coefficients, shown in Figure 2, of course, are similarly large in comparison to the k = 0.5 and 5.0 results. Figure 2

also compares exact small disturbance results (GTRAN2) with those obtained in the low-frequency approximation; for sufficiently large reduced frequencies the latter yield inaccurate amplitudes as well as phase information.

The chordwise dependence of unsteady loading on flap deflection is best represented using nonlinear harmonic expansions. Calculations for the NACA 64A006 airfoil with an aft-mounted quarter chord flap were carried out for $M_\infty = 0.85$ and $k_{sc} = 0.24$ and $M_\infty = 0.80$ and $k_{sc} = 0.064$ assuming maximum deflection angles δ of 1°, 2° and 3° in each case (k_{sc} is the reduced frequency based on semichord). We stress that deflections greater than 1°, approximately, are on the order of the thickness ratio δ_0, thus falling outside the range where Ehlers' straightforward linearization [2] holds. While our neglect of higher harmonics also implicitly assumes "small" amplitudes, the account of mean flow distortion extends somewhat the applicability of the harmonic method to larger unsteady perturbations. For convenience introduce the functions C_{p_0}, $C_{p_1}^r$ and $C_{p_1}^i$ through $C_p = C_{p_0} + \varepsilon(C_{p_1}^r \cos\tau - C_{p_1}^i \sin\tau)$ and define $\mathcal{C}_p^{r,i} = \frac{\varepsilon}{\delta} C_{p_1}^{r,i}$. Figure 3 compares results of $M_\infty = 0.85$ and $k_{sc} = 0.24$ calculations with experiment [5] and with linear theory for a flap deflection of $\delta = 1^\circ$. The qualitative agreement obtained for this supercritical flow is good but precise results are difficult owing to wind tunnel wall interference and unsteady viscous interactions. Results of $\delta = 2^\circ$ and 3° appear in Figure 4. The unsteady loading is seen to vary linearly with changes in deflection angle, an observation not initially anticipated because, as previously indicated, $\delta > \delta_0$. This linearity also follows as a consequence of the extremely weak dependence of $C_{p_1}^{r,i}$ on ε. Similar calculations and results for the $M_\infty = 0.80$ and $k_{sc} = 0.064$ case are shown in Figure 5.

V DISCUSSION AND CLOSING REMARKS

This paper extends the scope of an available time-marching ADI method [3] to handle general unsteady motions and also generalizes an existing harmonic analysis tool [2] to handle large amplitude oscillations. Immediate applications using the former method include the modeling of sudden gust loadings, for example, while the latter scheme, for instance, allows us to define flutter boundaries using both frequency and amplitude parameters. Here the new computational algorithms are used to study the flow induced by the transonic oscillating flap systematically. The generalized ADI method reproduces the shock motion freeze in the limit of large reduced frequency, as anticipated by Landahl [1], and also illustrates the sizable net lifts and moments that characterize aerodynamically undesirable low-frequency oscillations. Moreover the results of the time-marching algorithm developed here illustrate various inaccuracies associated with low-frequency models and suggest that their use be limited to reduced frequencies (based on chord) of less than 0.2, say. Calculated results for the $\delta = 1^{o}$ case (e.g., see Figure 1) indicate that the mean flow does not change with frequency.

The nonlinear harmonic method was used to study the effect of flap deflection on unsteady chordwise loading for several low reduced frequencies. The inviscid results, unhampered by the effects of wind tunnel wall interference and unsteady viscous interactions, indicate that the local unsteady loading varies linearly with respect to changes in deflection angle, even though the deflections are not small. This question was also partially pursued by Tijdeman [5]. Experiments were conducted to establish the range of possible maximum flap deflection amplitudes over which a linear relationship existed between δ and the resulting unsteady loading.

Linearity was established but, unfortunately, limitations in the laboratory set-up allowed only maximum values of 1° for consideration. For such small deflections the buffer furnished by the boundary layer reduces flap effectivity and the extent of "inviscid nonlinearity" could not be truly assessed. However the results of the present computations support Tijdeman's conclusions: the observed linearity is significant and may be of some consequence in the engineering of aircraft controls. Tijdeman further reports that "the mean steady pressure distributions correspond reasonably well with the steady pressure distributions ..... obtained on the nonoscillating model" (this observation is based on a flap deflection of 1° with low reduced frequencies and supercritical Mach numbers). Again our computations support this conclusion (e.g., see Figures 1, 4 and 5). Additional numerical experiments, not reported here, indicate that for mildly supercritical flows the back-interaction effect is a weak one and that integrated normal forces and pitching moments respond sinusoidally.

The two numerical algorithms presented here for unsteady transonic flow with shockwaves provide useful vehicles for unsteady aerodynamic calculations and require only simple modifications to existing well used computer codes. In this paper they are systematically applied to the study of effects induced by changes in flap angle and oscillation frequency in the case of a symmetric unpitched airfoil. The results agree with some physical arguments of Landahl [1] and the experimental work of Tijdeman [5] but they do not bear the limiting restriction to small flap deflections.

VI ACKNOWLEDGMENTS

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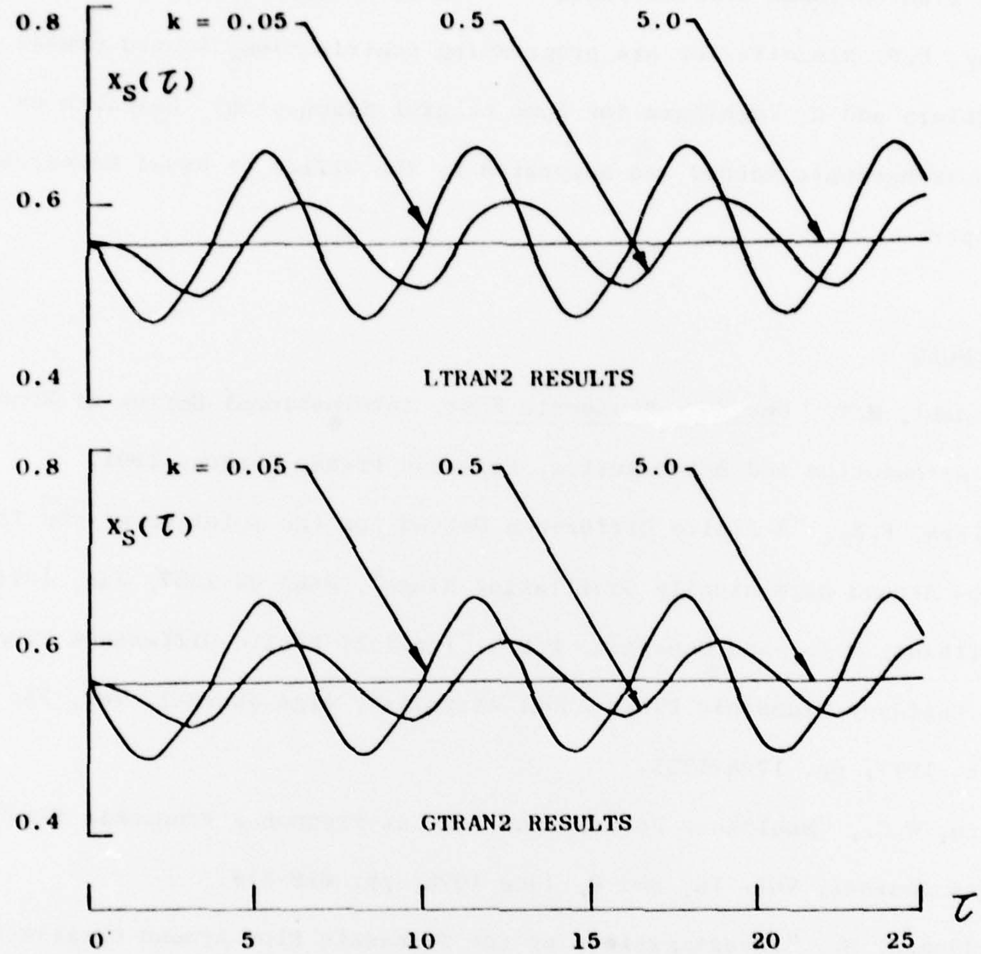

FIG. 1. SHOCK LOCATION $x_S(\tau)$.

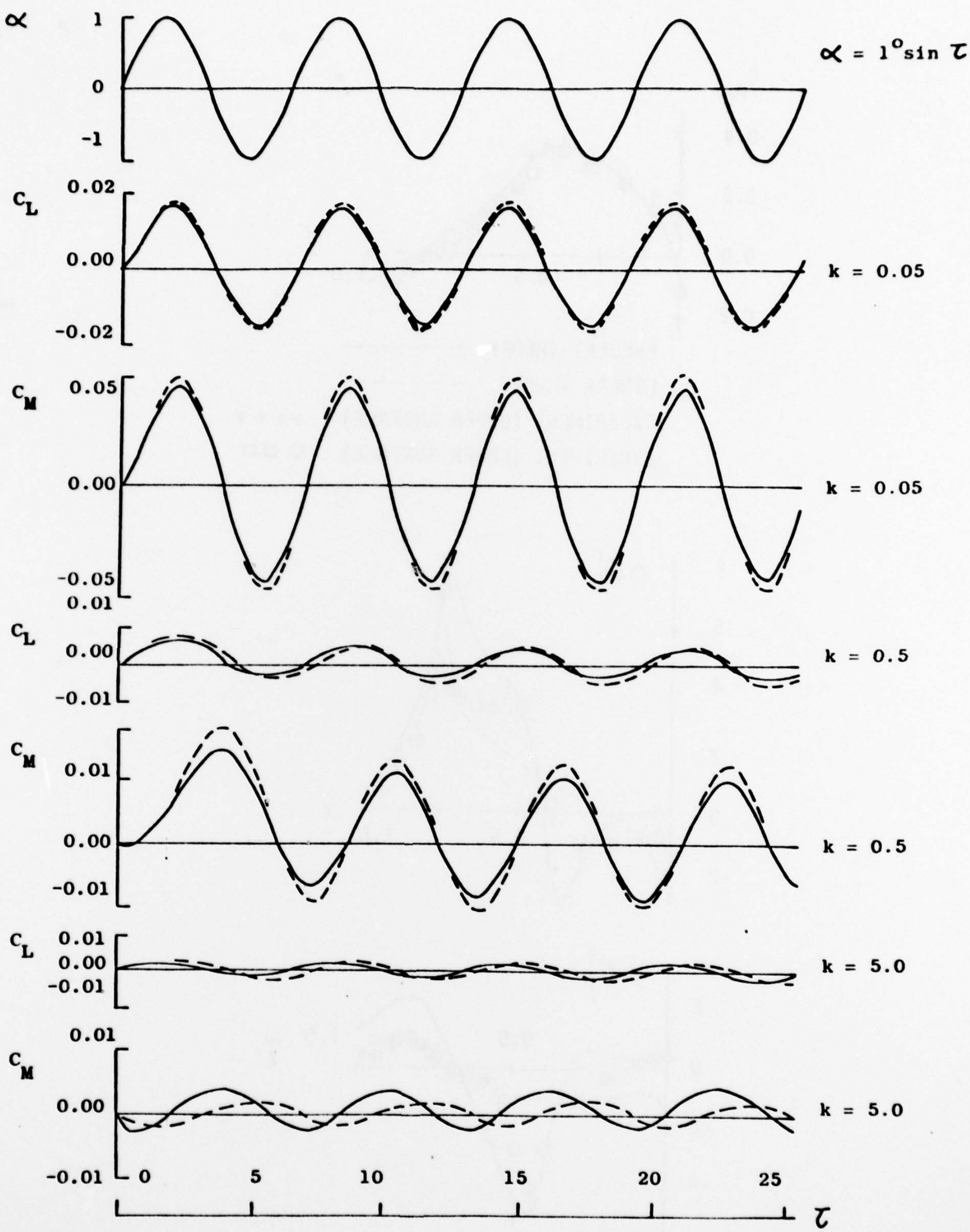

FIG. 2. FLAP OSCILLATIONS, GTRAN2 ———— , LTRAN2 - - - - -

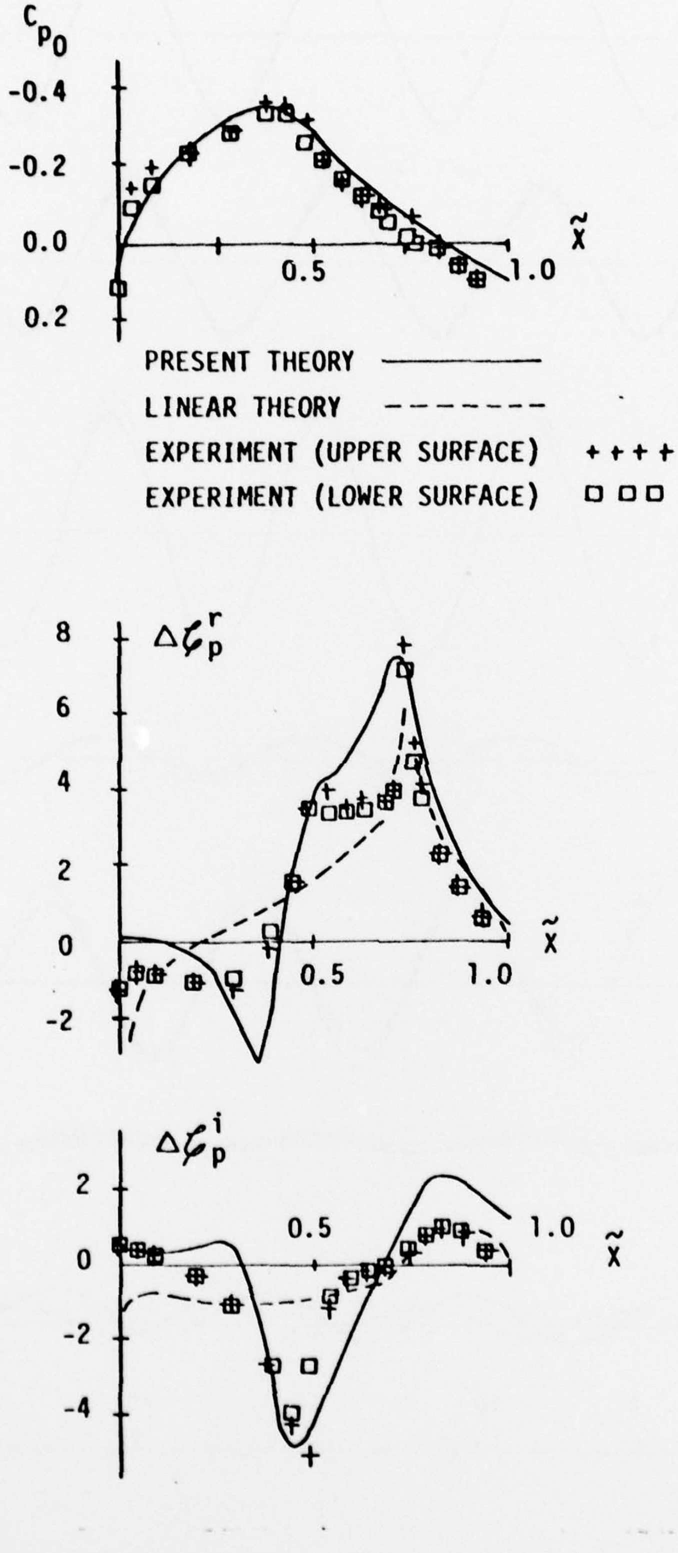

FIGURE 3. MACH 0.85, REDUCED FREQUENCY 0.24, FLAP DEFLECTION 1°.

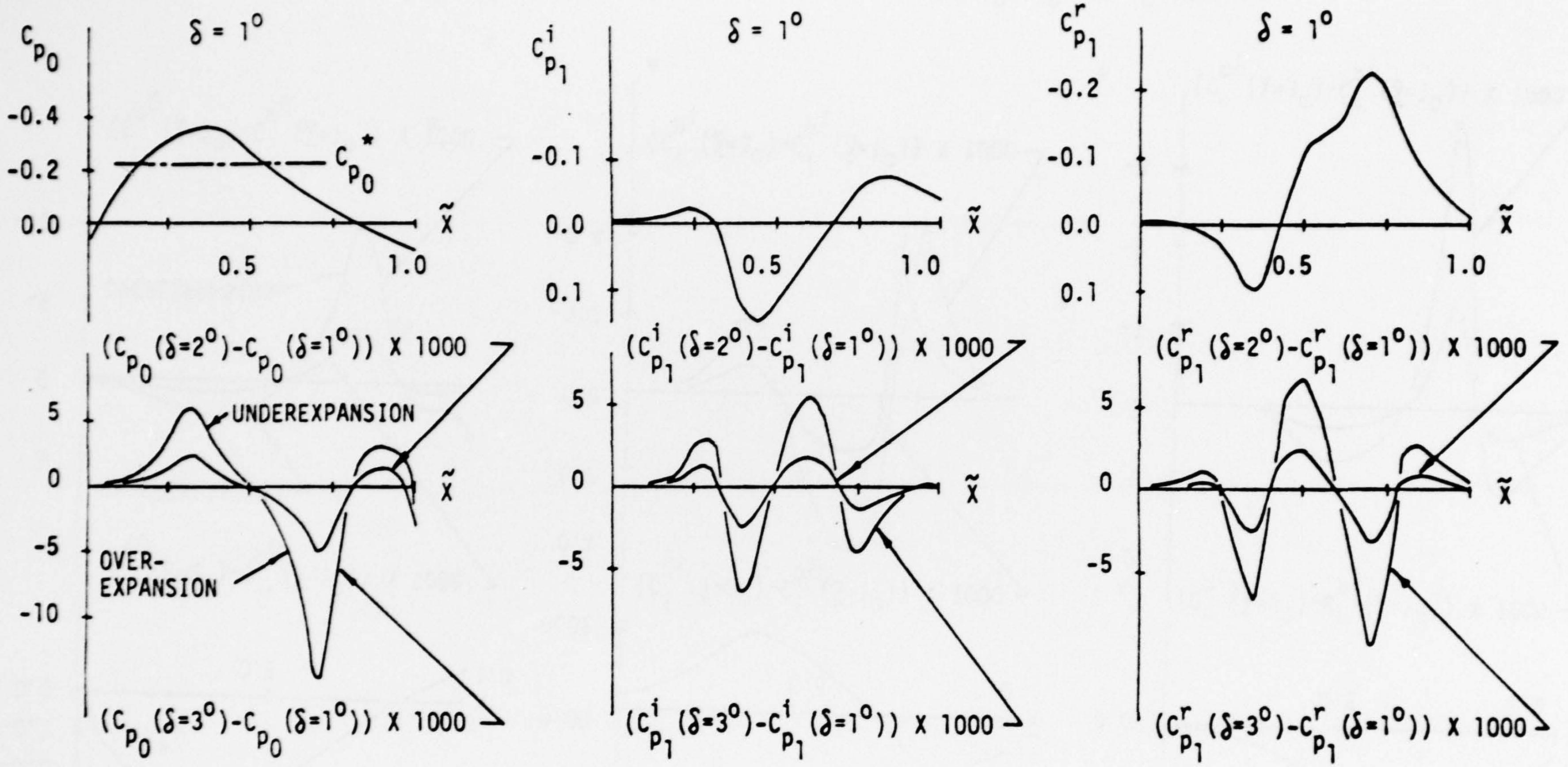

FIGURE 4. MACH 0.85, REDUCED FREQUENCY 0.24, FLAP DEFLECTIONS 1^o, 2^o AND 3^o CASES. (NONLINEAR HARMONIC METHOD)

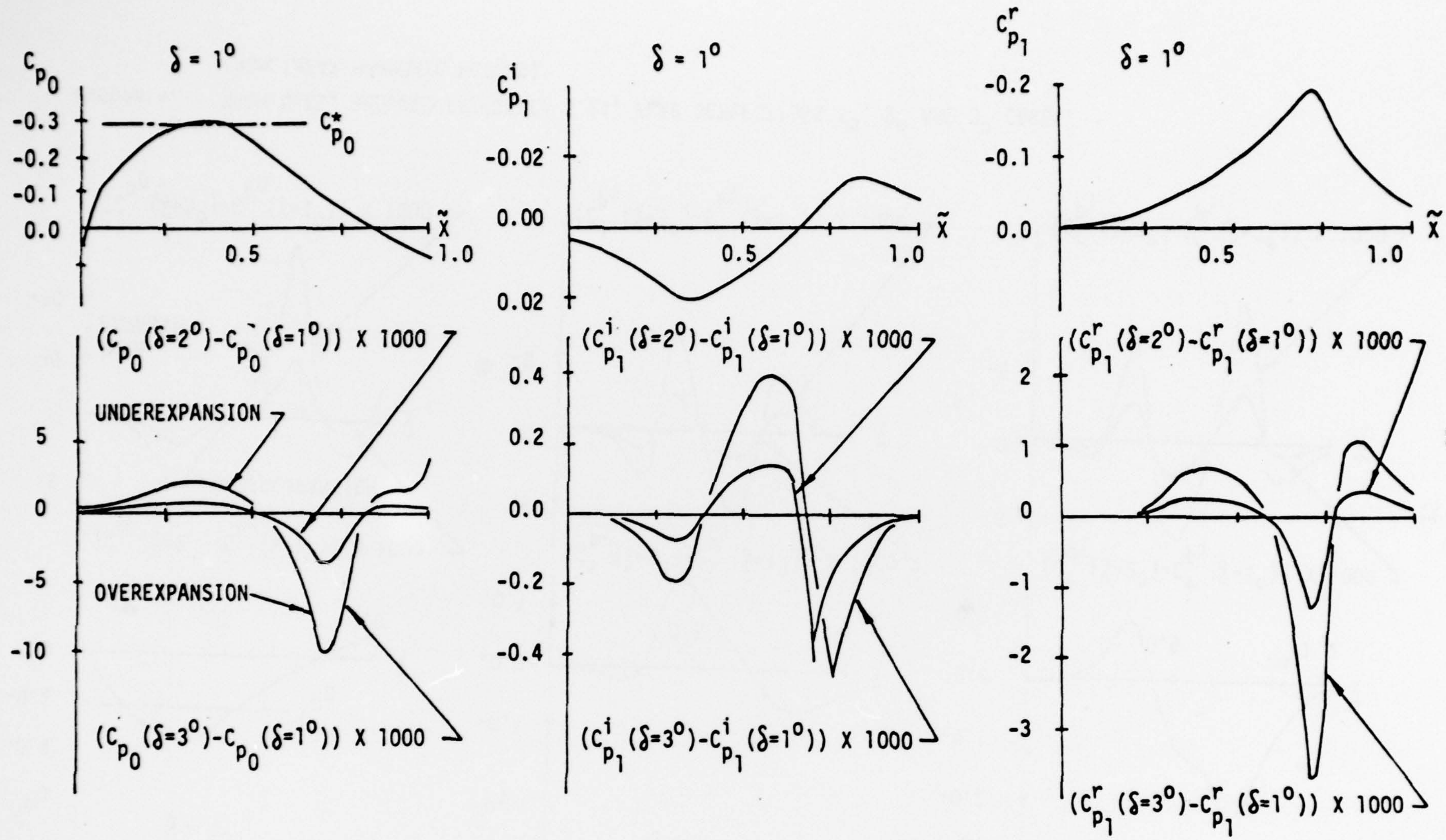

FIGURE 5. MACH 0.80, REDUCED FREQUENCY 0.064, FLAP DEFLECTIONS 1^o, 2^o AND 3^o CASES. (NONLINEAR HARMONIC METHOD)